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# A Method for Eliminating the Effects of Aliasing When Acquiring Interior Ballistic Data From Regenerative Liquid Propellant Guns

Todd E. Rosenberger  
James DeSpirito

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## 1. INTRODUCTION

The acquisition of interior ballistic data such as propelling gas pressure, projectile acceleration, and projectile-bore interactions in conventional propulsion systems has become routine at the U.S. Army Research Laboratory (ARL). These measurements are necessary to evaluate existing weapon systems and to validate newly formulated interior ballistic models. However, with the emergence of advanced propulsion concepts such as regenerative liquid propellant technology, the instrumentation systems needed to acquire and process these ballistic data have changed. Unlike the ballistic parameters observed in conventional propulsion systems, high frequency oscillations have been observed in ballistic data acquired from Regenerative Liquid Propellant Gun (RLPG) systems. The effects of these oscillations on projectile integrity, projectile payloads, and system wear is a key technical issue in the fieldability of these systems. In order to make any judgments concerning the effects of these oscillations, it is necessary to have some knowledge concerning their frequency and amplitude content. This fact places a great deal of importance on instrumentation and data acquisition practices. Appropriate data sampling rates and acquisition system bandwidths become paramount to acquiring accurate ballistic data.

Experimental investigation of interior ballistic events often requires a precise frequency spectrum analysis of data. This is particularly true in the study of high frequency pressure oscillations in the liquid propellant gun. Unfortunately, a phenomenon known as aliasing can severely bias the frequency spectrum of recorded data. In this report, aliasing is demonstrated with respect to regenerative liquid propellant gun data, and a standardized procedure is outlined to limit its effect. An analysis is put forward which quantifies the frequency and amplitude limitations associated with the frequency spectrum analysis routinely performed on this data.

## 2. EFFECT OF ALIASING

Before any waveform can undergo digital signal processing, it must be sampled. The rate at which the waveform is sampled determines how close the discrete representation is to the original analog waveform. The rule regarding adequate sampling of a waveform is popularly known as the Nyquist Criterion (Marshall 1990; Ramirez 1985). It states that it is necessary to sample a waveform at least twice per cycle in order to know its true frequency. In other words, there must be at least two samples per cycle for any frequency component you wish to resolve. If the sampling rate is less than twice the highest frequency component, then aliasing will occur.

The Nyquist Criterion can be verified through a simple experiment. By sampling sinusoids of increasing frequency while maintaining a constant sampling rate, the Nyquist Criterion, and in turn aliasing, can be demonstrated. As the sinusoid's frequency increases, a frequency will be reached such that samples occur at less than 2 per cycle. At this frequency (Nyquist frequency), aliasing can be observed. Figure 1 shows what will happen if a signal is digitized at a rate less than 2 samples per cycle. As seen in the figure, the digitized signal will have a lower apparent frequency than the original waveform.

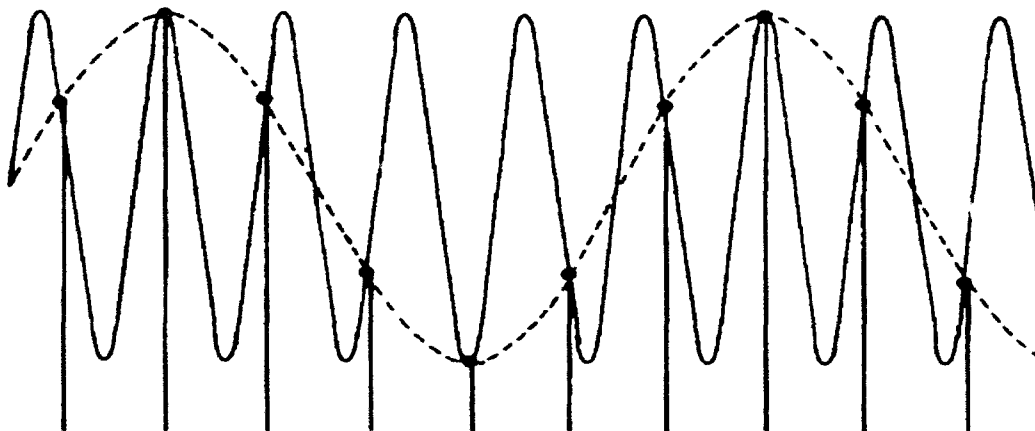


Figure 1. A Waveform Sampled At Less Than The Nyquist Rate.

This phenomenon can also be seen in the frequency domain where the spectral components can be observed to move out to the edges of the magnitude display as the frequency is increased. At the Nyquist frequency (half the sampling rate), the spectral components fold around the edges of the Fast Fourier Transform (FFT) magnitude display and can be seen at the lower frequencies. This is aliasing, which is the representation of a high-frequency component by a lower-frequency component.

This experiment is represented in Figures 2-6. Figure 2 shows the FFT representation of a 50 kHz sinusoid sampled at 200 kHz. Figures 3 and 4 show the corresponding FFT's for a 90 kHz and a 97 kHz sinusoid also sampled at 200 kHz. Note that as the frequency of the sinusoid approaches the Nyquist frequency, in this case 100 kHz, the spectral components move closer to the edges of the display. Figures 5 and 6 show the corresponding FFT's for a 105 kHz and a 120 kHz sinusoid also sampled at 200 kHz.

As the number of samples per cycle dropped below two, the spectral components folded over into the lower frequency area of the display (95 kHz and 80 kHz respectively). Likewise, if we were to sample a 250 kHz sinusoid at 200 kHz, its spectral components would be represented at 50 kHz. This experiment clearly demonstrates the effect of aliasing on a simple sinusoid. The next step is to investigate its effect on a waveform with a more complex frequency spectrum.

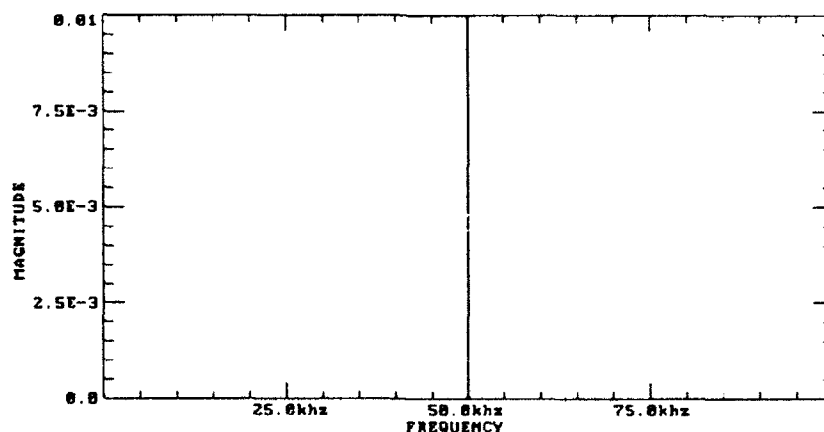


Figure 2. FFT of a 50 kHz Sinusoid Sampled at 200 kHz.

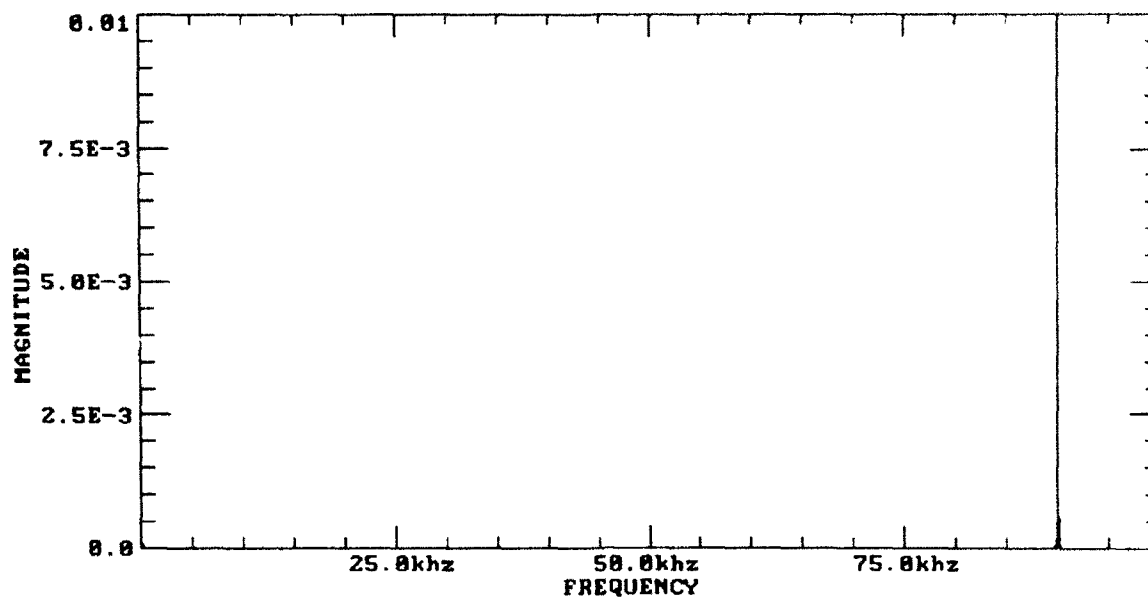


Figure 3. FFT of a 90 kHz Sinusoid Sampled at 200 kHz.

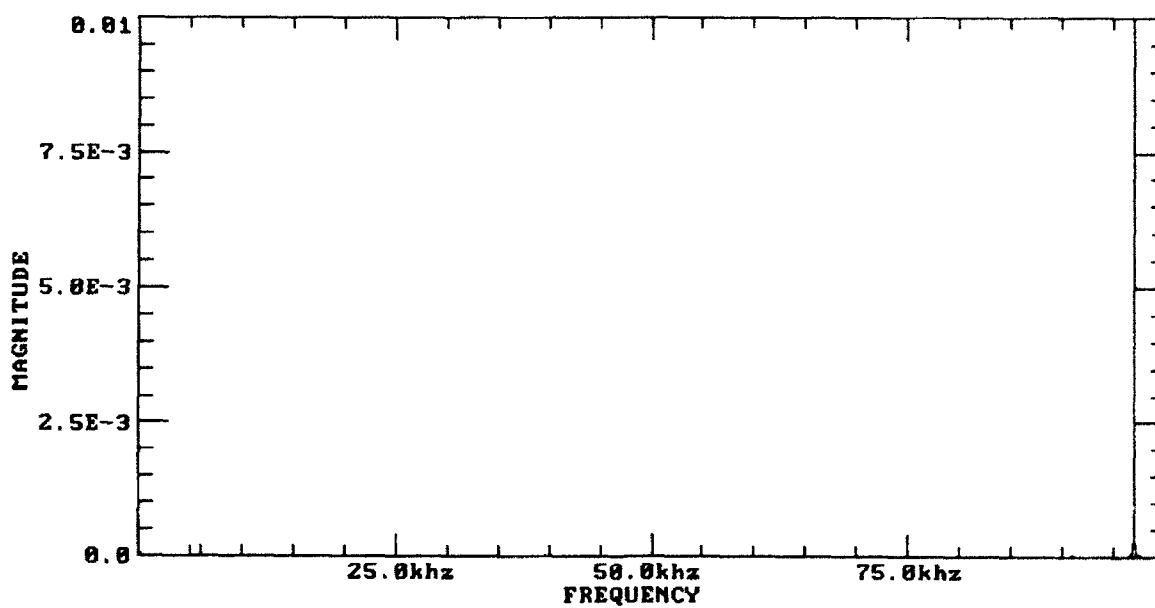


Figure 4. FFT of a 97 kHz Sinusoid Sampled at 200 kHz.

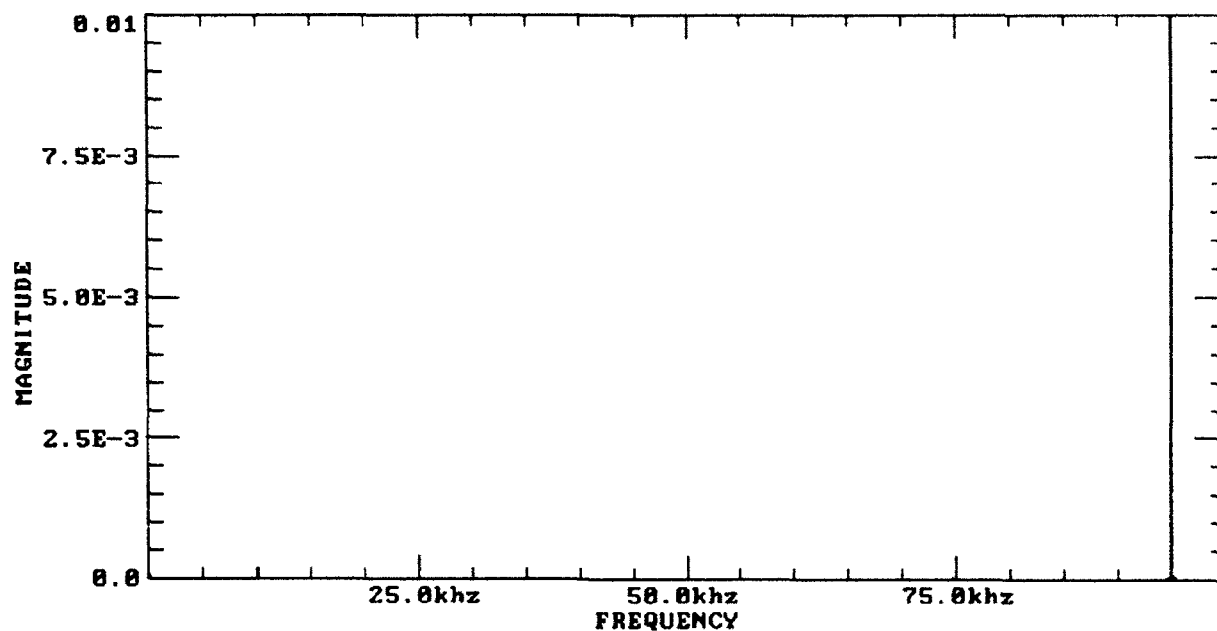


Figure 5. FFT of a 105 kHz Sinusoid Sampled at 200 kHz.

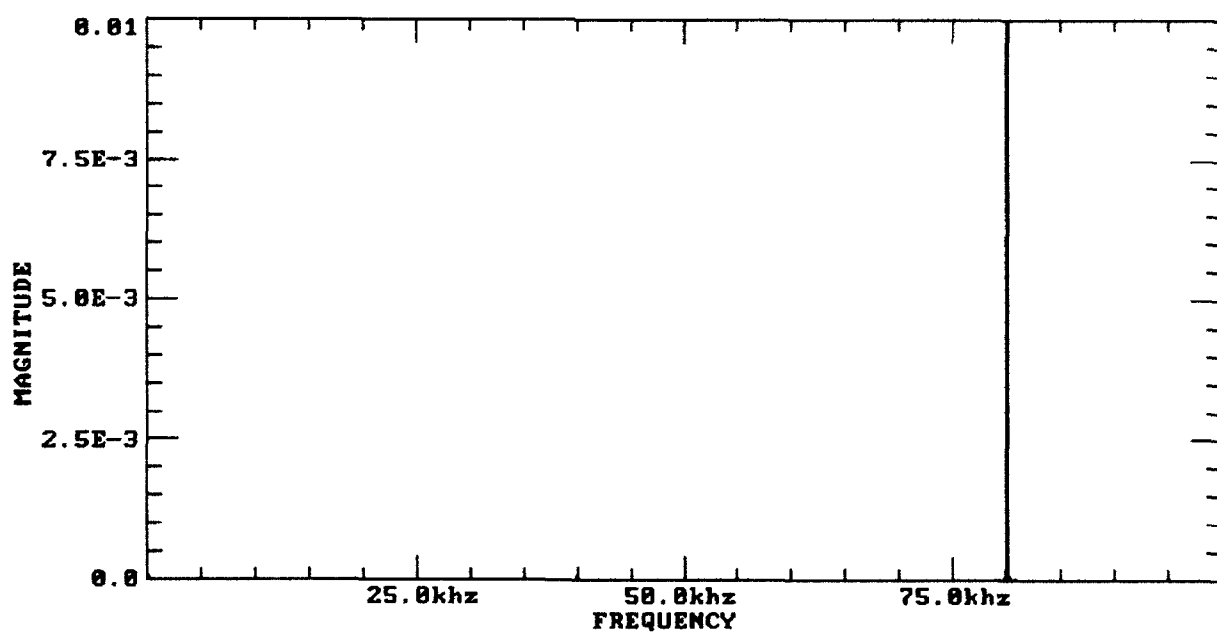


Figure 6. FFT of a 120 kHz Sinusoid Sampled at 200 kHz.

### 3. ALIASING IN RLPG TESTING

The acquisition system used to acquire the sinusoids in the previous experiment is the same system used to acquire interior ballistic data from RLPG testing at the ARL. The aliasing, or "foldover," effect demonstrated in the previous experiment also applies to much more complex spectral transients such as those encountered in the measurement of interior ballistic data in RLPGs. Figure 7 shows a chamber pressure representative of the data acquired from a 30-mm RLPG at the ARL. The pressure oscillations seen on this pressure-time (  $P-t$  ) curve contain a wide range of frequency components. These oscillations can range from a few kHz to near one-hundred kHz. However, effects of the pressure transducer, such as resonant frequency (Kistler 1991), result in much higher frequencies being present in the acquired data. Figure 8 shows an FFT (1 ms at peak) of a chamber pressure from a 30-mm RLPG firing. The data was acquired at 500 kHz, therefore the frequency on the plot shown extends up to the Nyquist frequency of 250 kHz. The resonant frequency for the Kistler 607C4 pressure transducer used in this test is nominally 250 kHz. As can be seen from Figure 8, there is a relatively dominant frequency which occurs at approximately 230 kHz and there is also quite a wide spectrum of data between 100 kHz and 200 kHz. The point of presenting this complex frequency spectrum is to demonstrate that there are frequencies in the spectrum that could potentially be aliased to lower frequencies if steps are not taken to alleviate this effect. If these frequencies were aliased, they could severely bias the frequency analysis of the pressure oscillations seen in Figure 7.

Aliasing is virtually inevitable when sampling analog waveforms with broad band frequency spectrums as in the case of the digital representation of RLPG data. In practice it is sometimes difficult to have a sampling rate that assures two samples per cycle for all frequencies in the spectrum. In most cases, however, there is a frequency at which the energy in the spectrum of the waveform drops below what can be considered a significant level. In order to resolve the frequency content of such an analog waveform, one need only be sure that a sampling rate is selected which ensures several samples per cycle



occur for the highest frequency of significance. Any aliasing that occurs is then below the level of consideration, or at least below the resolution of the acquisition system. The problem with this concept is that it is very difficult to determine this frequency.

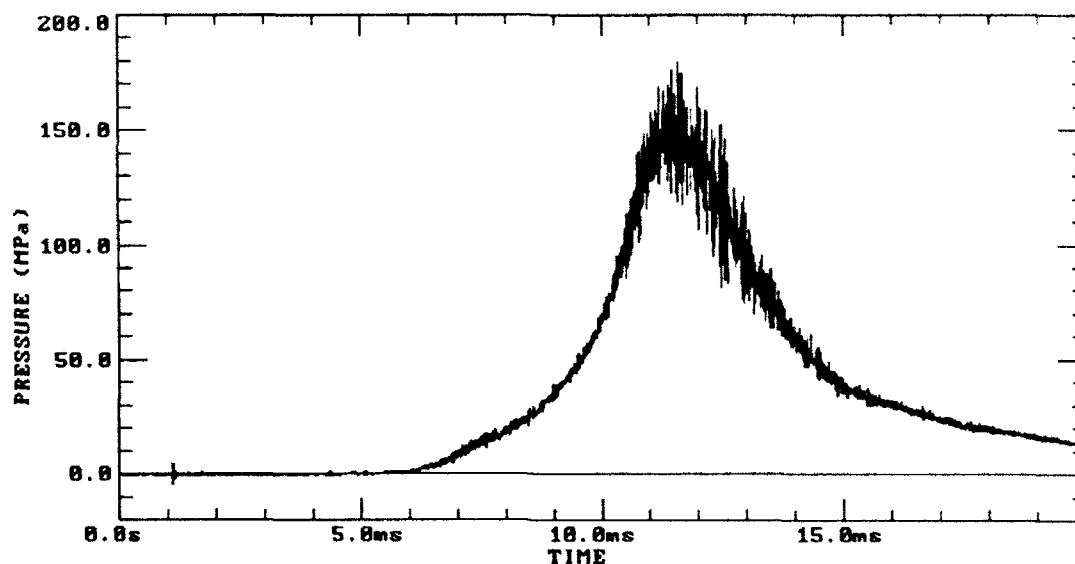


Figure 7. Chamber Pressure From a 30-mm RLPG.

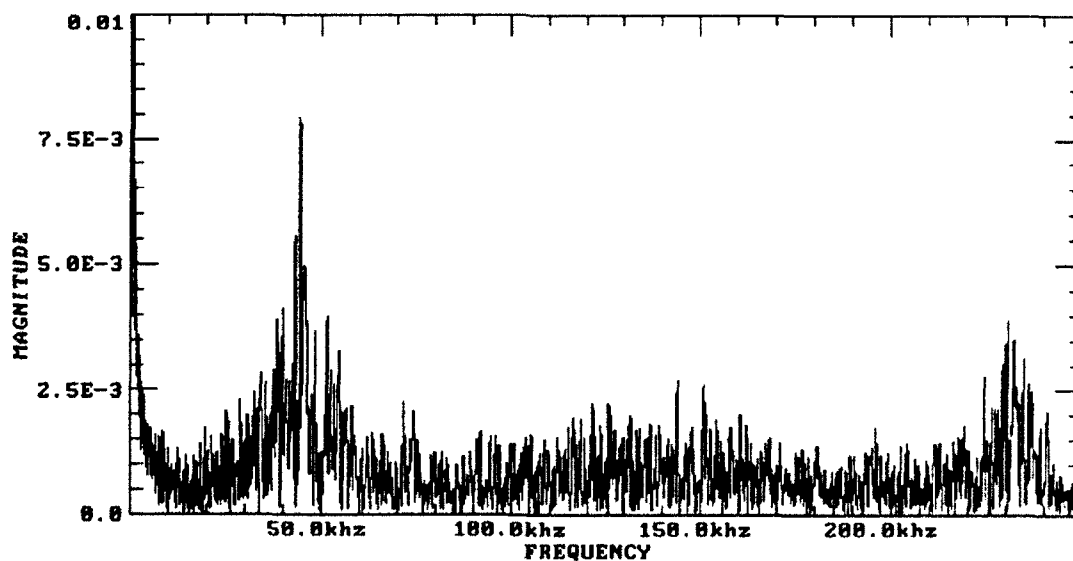


Figure 8. FFT of Pressure Above Sampled at 500 kHz.

The criterion for resolving the frequency content of the pressure oscillations observed in RLPG's has been considered. However, the amplitude of these oscillations must also be considered. It is a necessary condition to sample the waveform at least twice per cycle in order to resolve the frequency content of the waveform. However, this is not a sufficient condition to resolve the amplitude of the oscillations. Figures 9-11 serve to demonstrate that sampling at a few samples per cycle will not resolve the amplitude characteristics of a waveform. Figure 9 shows a 40 kHz sinusoid that was sampled at 100 kHz (2.5 samples/cycle). Obviously, the amplitude of the waveform has not been adequately resolved. Figure 10 shows a 40 kHz sinusoid that was sampled at 200 kHz (5 samples/cycle). The waveform's amplitude appears to be resolved satisfactorily but the digital representation does not exactly represent the shape of the original waveform. Finally, Figure 11 shows the same waveform sampled at 500 kHz (12.5 samples/cycle). The digital representation is much improved, but it still does not exactly represent the shape of the original waveform. In fact, one may have to sample a given analog waveform at 20 times the highest frequency in the spectrum in order to fully resolve the shape of the waveform (Marshall and Verdun 1990). Obviously, it is not practical to sample a waveform with frequencies in excess of 80 kHz (RLPG data) at such a high rate. However, it is generally not necessary to duplicate the waveform's exact shape. In most cases, it suffices to be able to resolve the frequency and the amplitude components of the

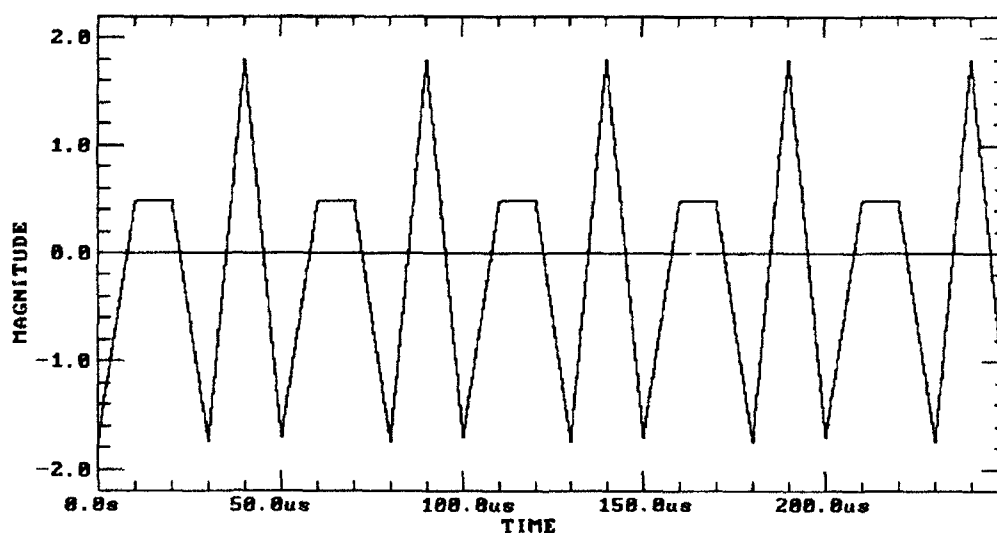


Figure 9. A 40 kHz Sinusoid Sampled at 100 kHz.

waveform. A general rule of thumb is to sample a given analog waveform at least 5 times per cycle in order to adequately resolve both the amplitude and the frequency content of the waveform.

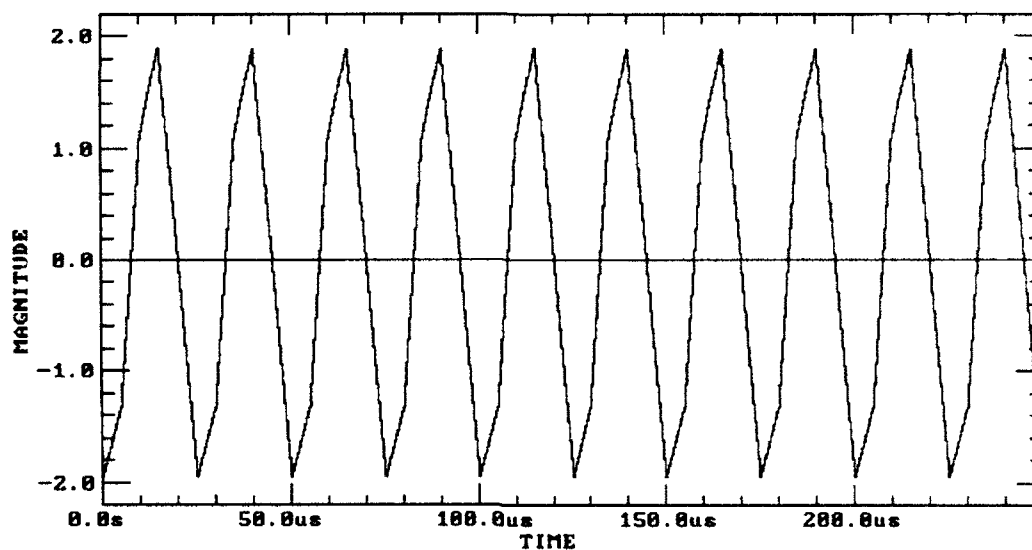


Figure 10. A 40 kHz Sinusoid Sampled at 200 kHz.

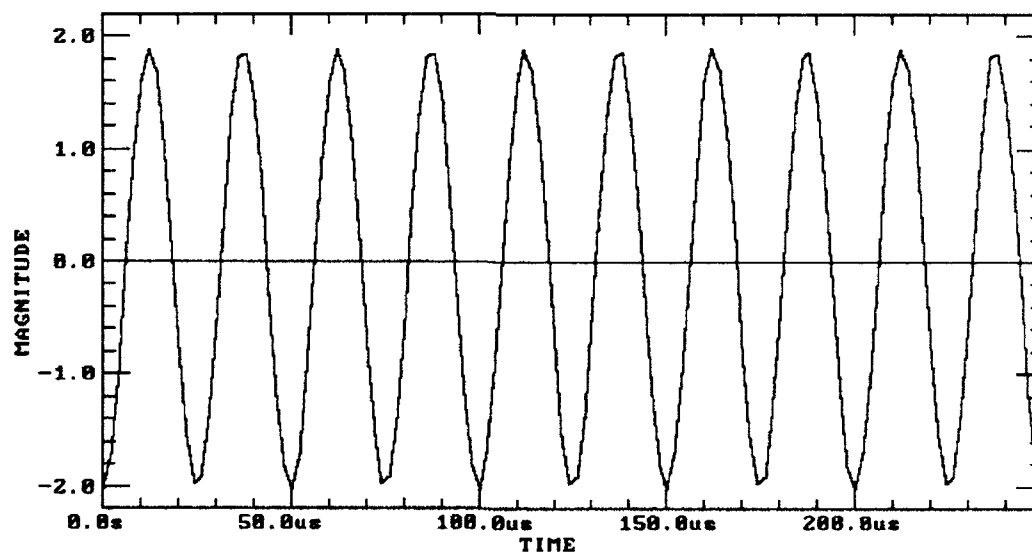


Figure 11. A 40 kHz Sinusoid Sampled at 500 kHz.

It is difficult to determine whether data acquired from RLPGs are high enough in frequency to cause aliasing. This is primarily due to the fast rise time and high resonant frequency of the pressure transducer (note Figure 8), and the uncertainty of how high into the frequency spectrum the pressure oscillations actually extend. Therefore, one cannot be assured that aliasing effects will be eliminated simply by using a very high sampling rate. To alleviate the effect of aliasing when recording data from a RLPG, it is imperative that the data be filtered before it is sampled.

The following test was conducted in order to demonstrate that aliasing does occur in the acquisition of RLPG data if steps are not taken to eliminate its effect. The ballistic data acquisition system (BALDAS II) used for acquiring RLPG data at the ARL was used to

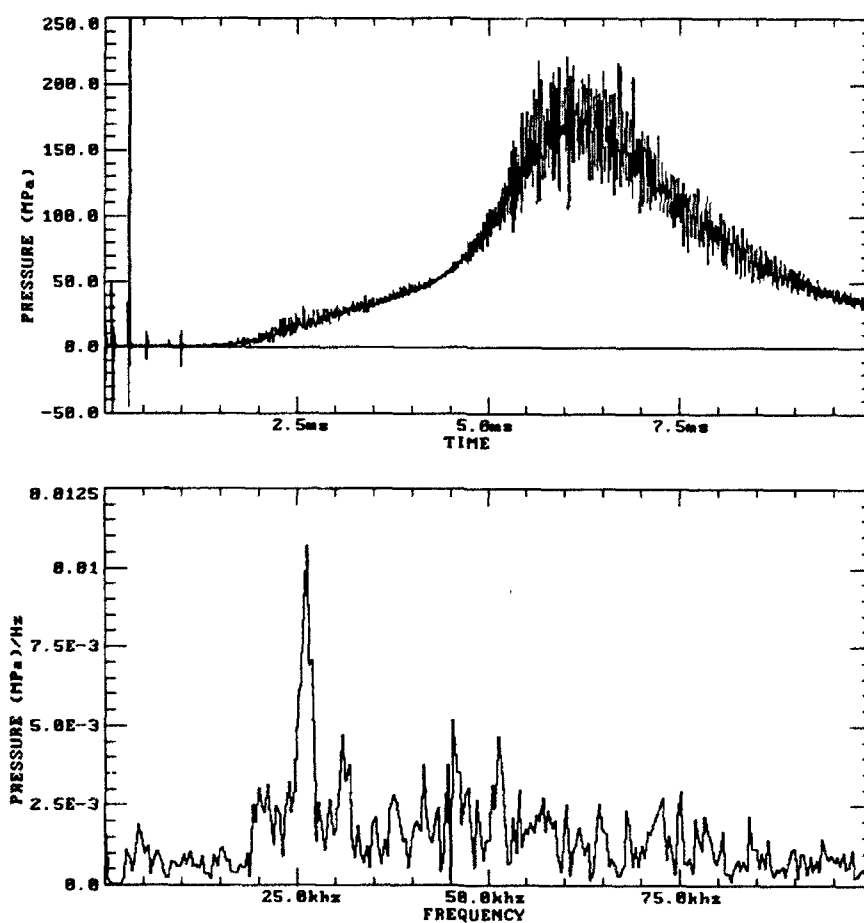


Figure 12. Chamber Pressure and Corresponding FFT Acquired at 200 kHz Without a Low-pass Filter.

acquire the data for this test. The data was also recorded on analog tape for future reference.

A chamber pressure was acquired at 200 kHz with, and without, an on-line low-pass filter at 80 kHz. Figure 12 shows the chamber pressure and its corresponding FFT for the case without the low-pass filter. Figure 13 shows the chamber pressure and the corresponding FFT for the case with the low-pass filter at 80 kHz. Note that when comparing the two chamber P-t curves, no significant difference can be seen. However, when comparing the information in the frequency spectrum, the data acquired without the low-pass filter appears to have much more energy across the entire spectrum. Recall Figure 8, which shows the FFT of a chamber pressure in a RLPG test that was sampled

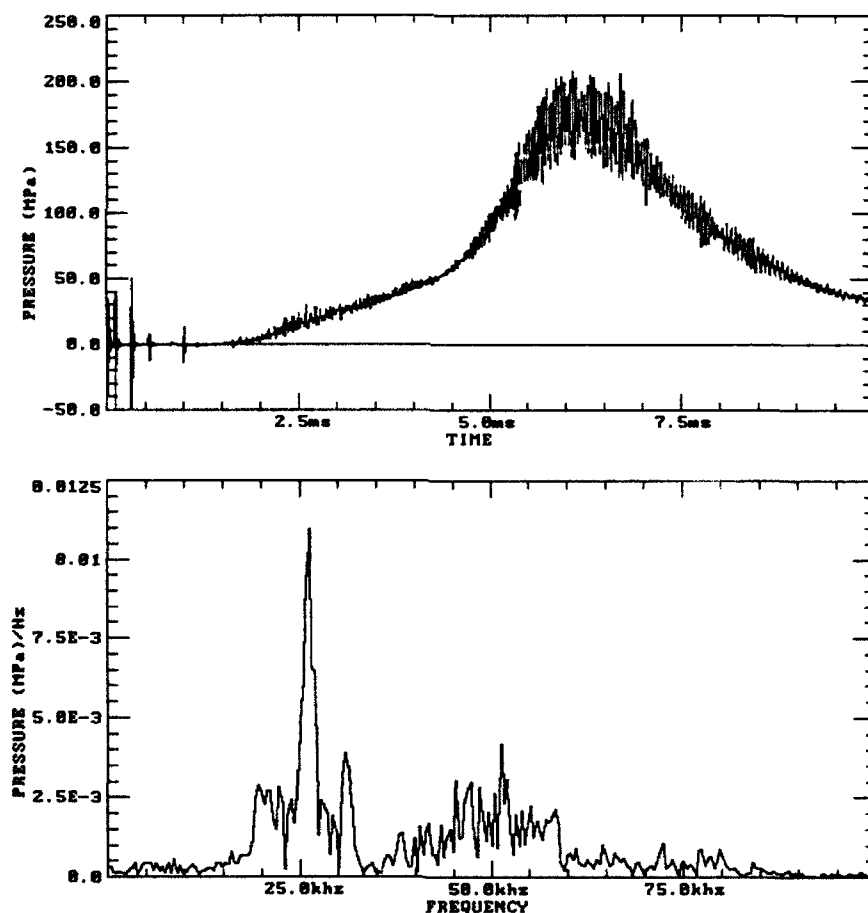


Figure 13. Chamber Pressure and Corresponding FFT Acquired at 200 kHz With an On-line Low-pass Filter at 80 kHz.

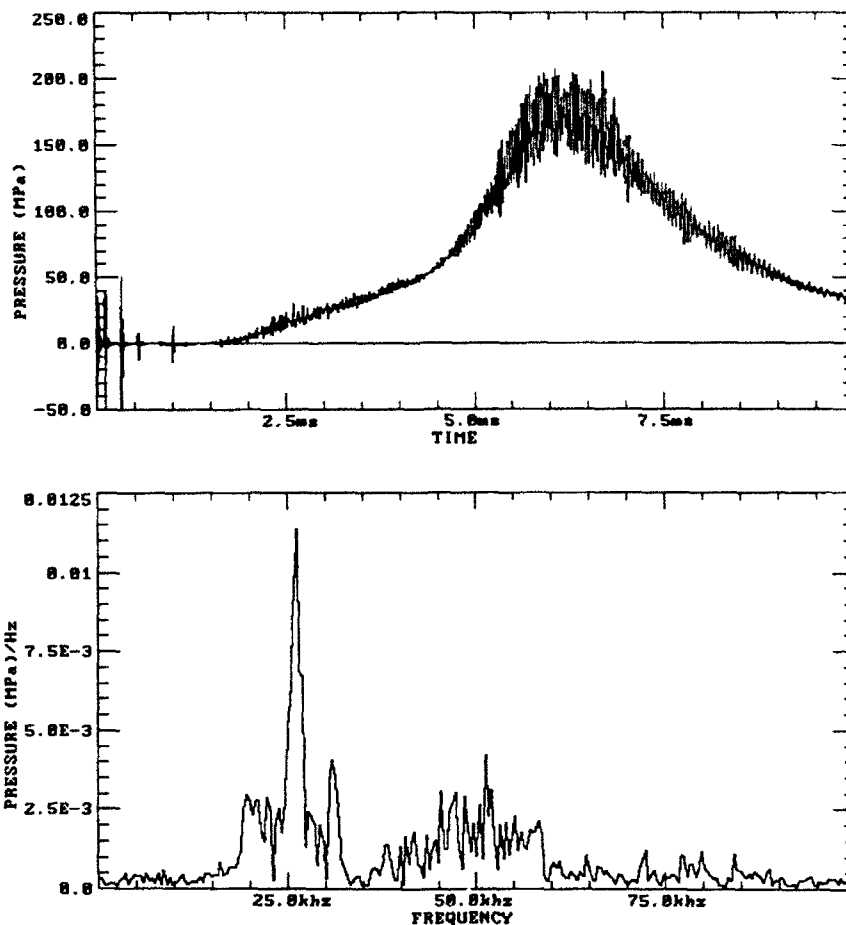


Figure 14. Chamber Pressure and Corresponding FFT Digitized at 400 kHz From Analog Tape With a Built in Low-pass Filter at 80 kHz.

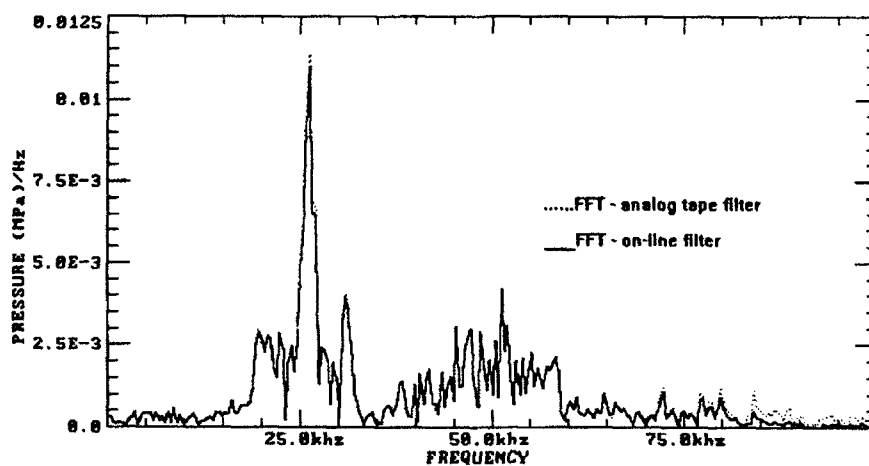


Figure 15. Comparison of FFT's For Case With On-line Low-pass Filter and Case With Analog Tape Low-pass Filter.

at 500 kHz. In the RLPG data that were acquired at 200 kHz, the frequencies above 100kHz would be aliased onto the lower frequencies. (e.g., 180 kHz to 20 kHz, 120 kHz to 80 kHz). By looking at Figure 8, it is evident that there are frequencies above 100 kHz that could easily add to the existing spectrum below 100 kHz, resulting in a spectrum similar to the one seen in Figure 12. Obviously, the techniques used to acquire data from RLPGs have a profound effect on any conclusions one can draw from a frequency spectrum analysis.

The chamber pressure acquired without the low-pass filter was then digitized from the analog tape at 400 kHz. The analog tape recorder also contained a built-in low-pass filter at 80 kHz in each play back card. Both the chamber pressure and the corresponding FFT are shown in Figure 14. As expected, the effect of aliasing was eliminated by the built-in low-pass filter at 80 kHz. Figure 15 shows a comparison between the FFTs from the on-line low-pass filter at 80 kHz and the analog tape recorder low-pass filter. Note that since the analog tape data was sampled at 400 kHz the spectrum actually ends at 200 kHz. However, for purposes of comparison, it was only plotted to 100 kHz. The only difference appears to be in the cutoff characteristics of the two filters. The on-line low-pass filter appears to have sharper cutoff characteristics. However, in either case, the filter served to eliminate the effect of aliasing.

#### 4. STANDARDIZED PROCEDURE

The previous paragraphs have demonstrated how aliasing can effect the validity of data recorded from RLPGs. The use of a filter to alleviate the effect of this phenomenon has been demonstrated. Based on this demonstration, a standardized procedure has been instituted at the ARL for use when acquiring RLPG data. Due to hardware limitations within the acquisition system, a 200 kHz sampling frequency per channel is the maximum that can be used to acquire the large number of channels required for instrumenting a RLPG. In addition, a set of 20 low-pass filters with relatively sharp cutoff characteristics would be needed in order to filter the data on-line. These filters were unavailable within present resources and a substantial investment would be required to procure them.

An alternative method of acquiring RLPG data is available. As previously demonstrated, RLPG data can be recorded on analog tape and then digitized to generate a discrete representation. Two factors make this option attractive. The first is the fact that it is possible to sample the analog waveforms from the analog tape at a faster rate (400 kHz in this case) than when acquiring the data in real-time. Second, the analog tape recorder play back cards each have a low-pass filter at 80 kHz built into them, which can be used to prevent aliasing effects. In addition, by sampling at 400 kHz and filtering at 80 kHz, the rule for sampling a waveform is maintained. If you will recall, a general rule of thumb is to sample a given analog waveform at least 5 times per cycle in order to adequately resolve both the frequency and amplitude content of the waveform. The procedure adopted is outlined below.

1. Acquire RLPG data on-line at 200 kHz to see the general waveform characteristics in real-time.
2. Record RLPG data on analog tape concurrently for future reference.
3. Digitize RLPG data from analog tape at 400 kHz to eliminate aliasing.

In a case such as when the acquisition system's sampling rate is limited and a large number of on-line filters is not available, the above solution serves to eliminate the effect of aliasing while adequately resolving the amplitude and frequency content of the waveform. However, due to the cutoff characteristics of the low-pass filter, some attenuation at frequencies near cutoff does occur.

## 5. FREQUENCY AND AMPLITUDE LIMITATIONS

Due to the fact that ideal filters do not exist, there will always be some attenuation of frequencies just below the cutoff frequency of the low-pass filter. It is very important to



Table 1. Comparison of Filter Cutoff Characteristics.

Frequency (kHz)	On-line Magnitude	Analog Tape Magnitude	Percent Difference ( % )
10	7.3	6.8	6.8
20	7.2	7	2.8
30	7.1	7.4	4.1
40	6.8	6.7	1.5
50	6.5	6.8	4.4
60	6.2	6.4	3.1
70	6.3	5.5	12.7
80	6.6	5.2	21.2
90	6.8	4.2	38.2
100	7	2.5	64.3
110	6.9	1.4	79.7
120	7.1	0.7	90.1

quantify the effect that this filter has on the amplitude content of the RLPG data. In order to quantify the cutoff characteristics of the built-in filter in the analog tape recorder play back cards, the following test was performed. The acquisition system previously described was used to acquire sinusoids of a single frequency ranging from 10 kHz to 120 kHz at a sampling frequency of 500 kHz. Each sinusoid of known frequency and amplitude was also recorded on analog tape and then digitized at 400 kHz. An FFT of 256 points was then performed on each pair of signals (on-line 500 kHz, digitized 400 kHz) and their amplitudes were compared. Table 1 shows the results of this test.

Based on this test, the following statements can be made concerning the limitations of the prescribed acquisition method. The frequency content of the data is accurate to 80 kHz, which is the cutoff frequency of the low-pass filter. However, due to the attenuation

of frequency components near the cutoff frequency the accuracy of the waveform's amplitude is only considered to be acceptable to 60 kHz. Beyond 60 kHz we cannot make any conclusions concerning the amplitude of the data with any confidence.

## 6. SUMMARY AND CONCLUSIONS

The effects of pressure oscillations on projectile integrity, projectile payloads, and system wear is a key technical issue to the LP community. In order to make any judgements concerning the effects of these oscillations, it is necessary to have some knowledge concerning their frequency and amplitude content. The importance of acquisition system parameters such as sampling rate and signal conditioning, are paramount to the measurement of data from RLPG systems. The phenomenon of aliasing was defined and demonstrated. The minimum sampling requirements were outlined. A general rule of thumb is to sample a given analog waveform at least 5 times per cycle in order to adequately resolve both the frequency and amplitude content of the waveform. The need to filter data before sampling to prevent aliasing was also demonstrated in a RLPG environment. The procedure used at the ARL to acquire RLPG data was outlined and both the frequency and amplitude limitations were addressed. The system used to acquire RLPG data at the ARL is accurate for frequencies up to 80 kHz. Due to attenuation caused by the low-pass filter involved in preventing aliasing, the amplitude of the waveform is accurate to 60 kHz.

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